Nuclear astrophysics at LUNA: recent results

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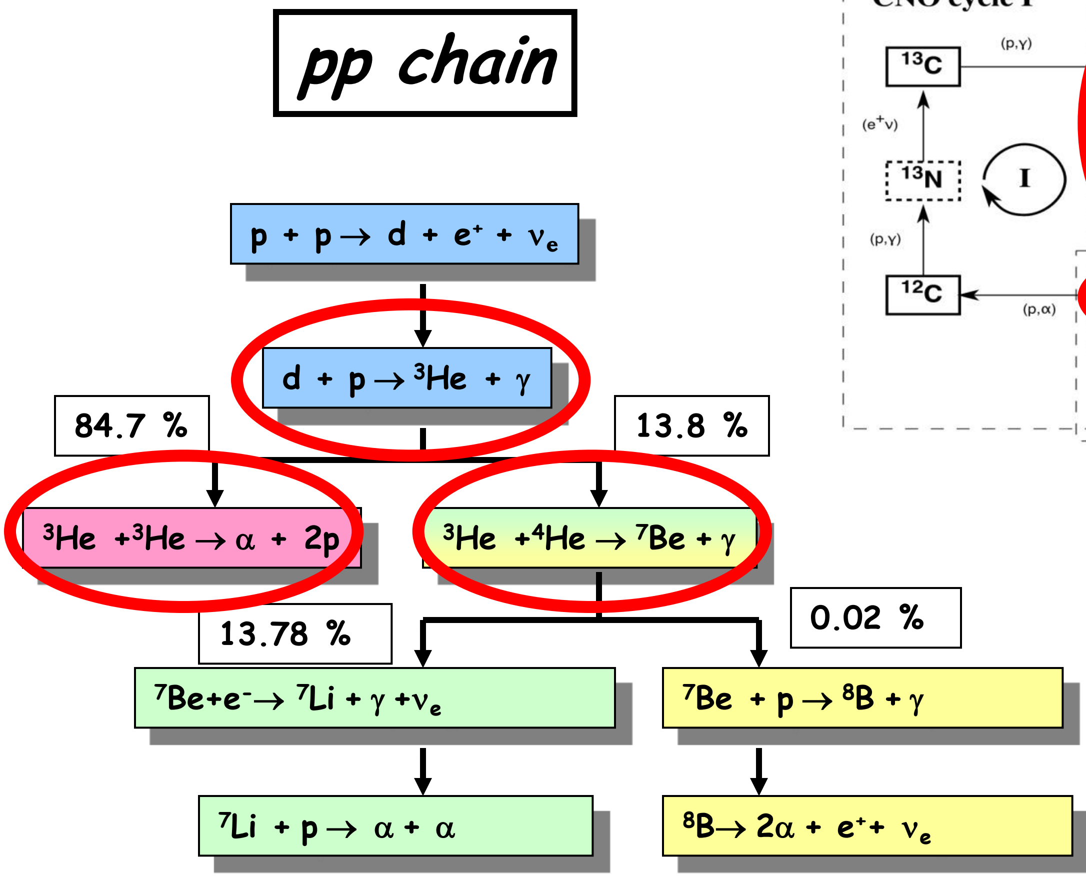
Laboratory
Underground
Nuclear
Astrophysics

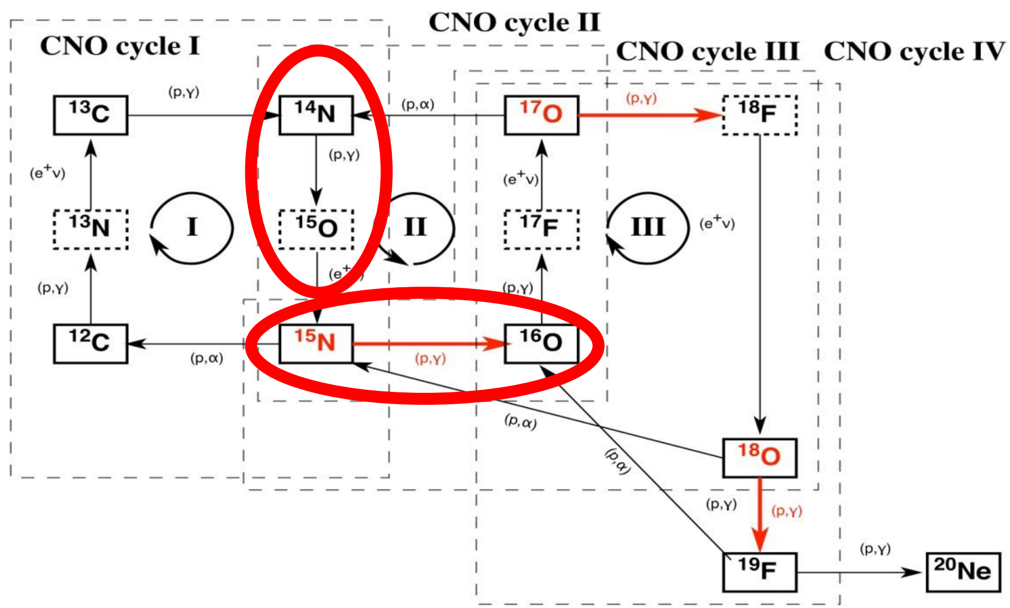
Outline:

- The Luna Experiment: most important results
- On-going measurements and future perspectives

Hydrogen burning

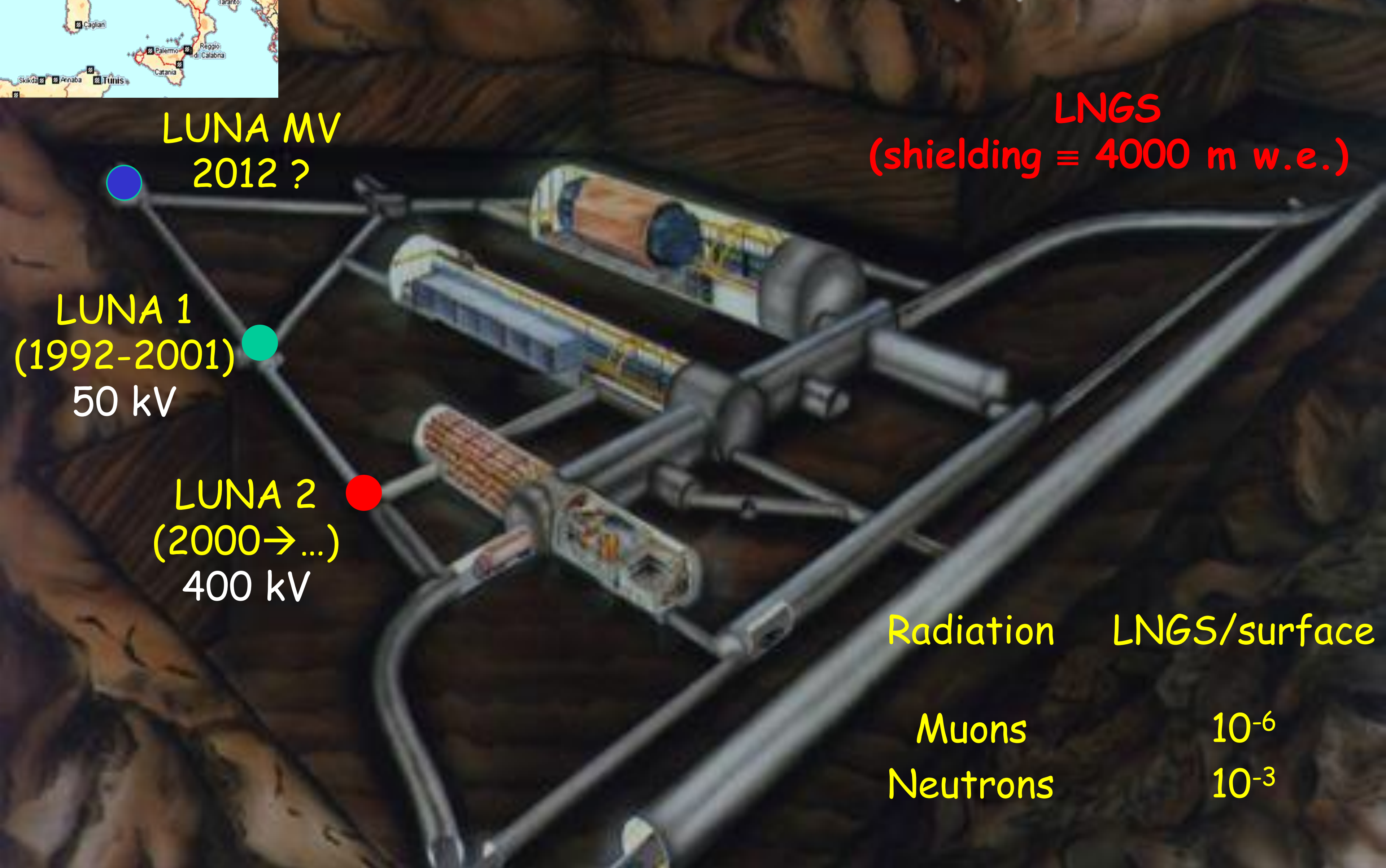
Produces energy for most of the life of the stars





$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e + 26.73\ MeV$$

Laboratory for Underground Nuclear Astrophysics



Radiation	LNGS/surface
Muons	10^{-6}
Neutrons	10^{-3}

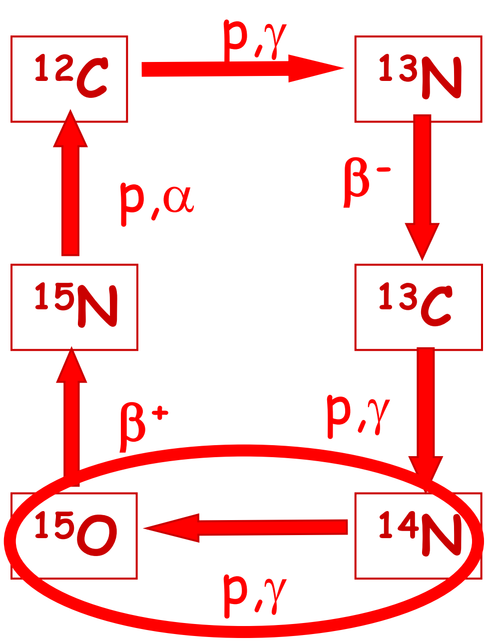
CNO Cycle

$T > 1.6\ 10^7$ K M>1.1 Solar masses

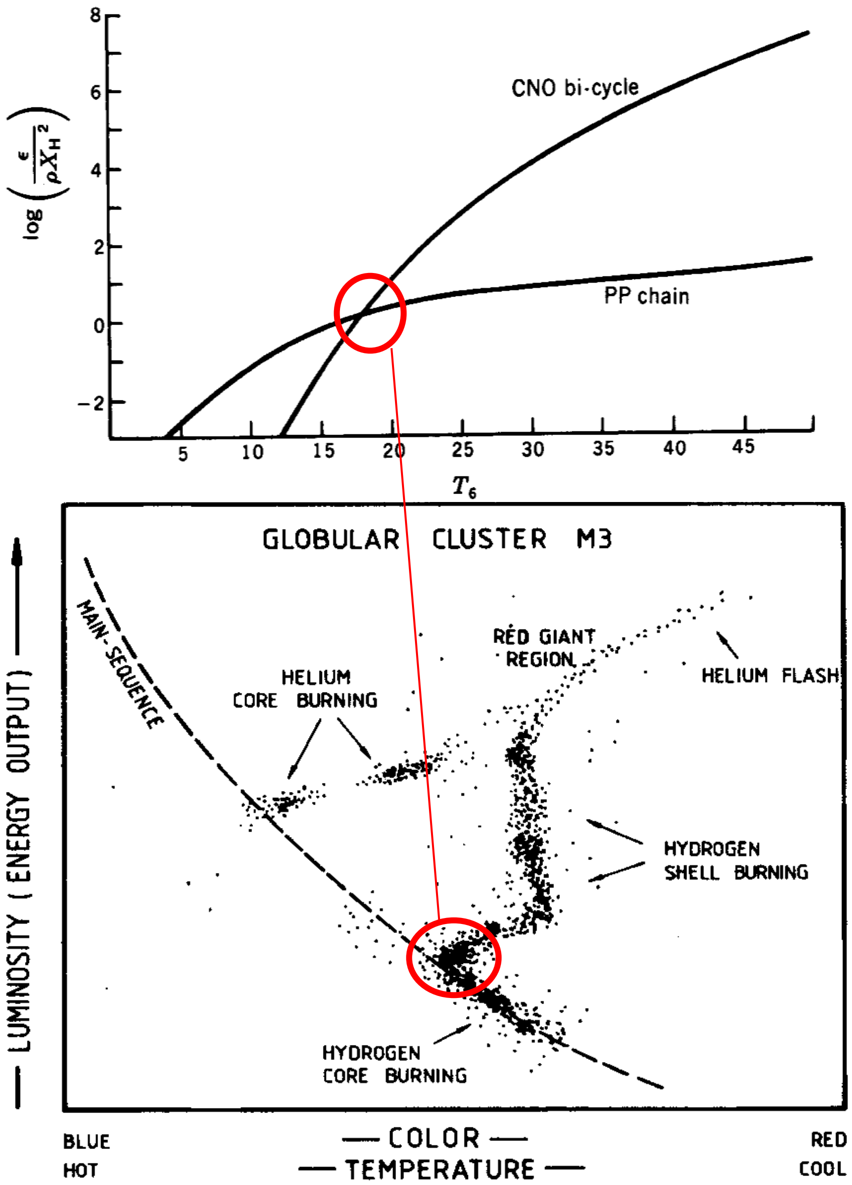
$^{14}N(p,\gamma)^{15}O$ is the slowest reaction and determines the rate of energy production

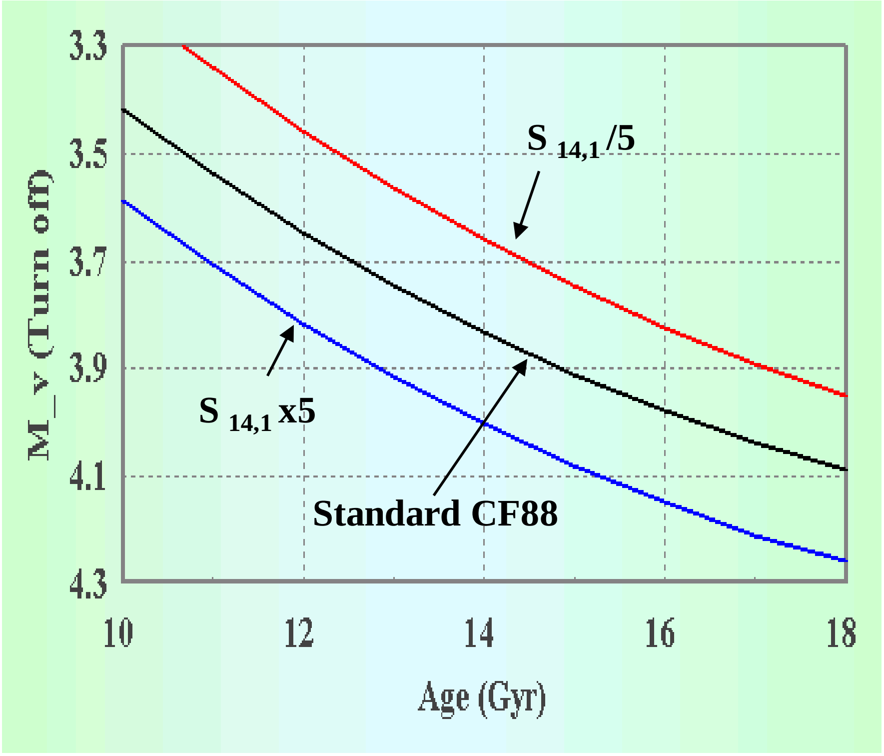
Its cross section influences:

- CNO neutrino flux→ solar metallicity
- Globular cluster age

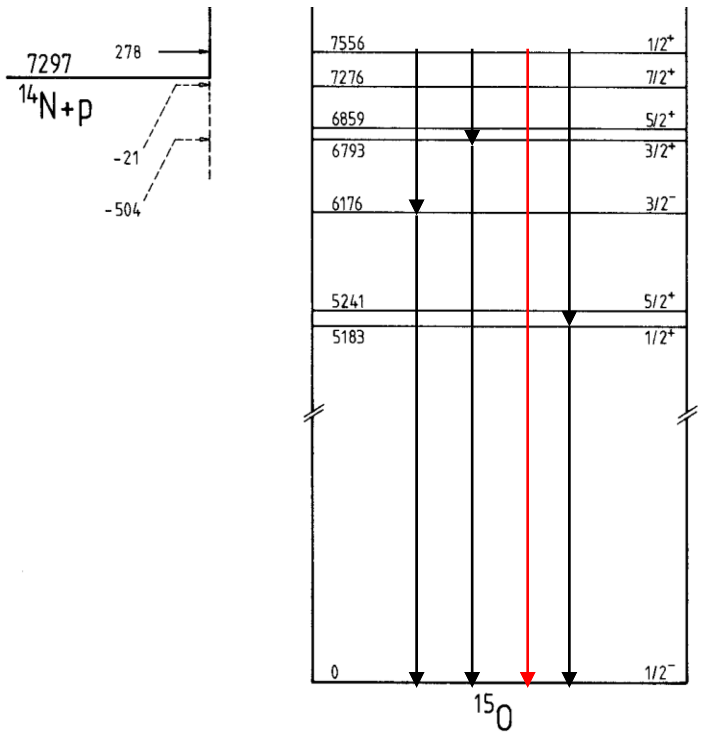


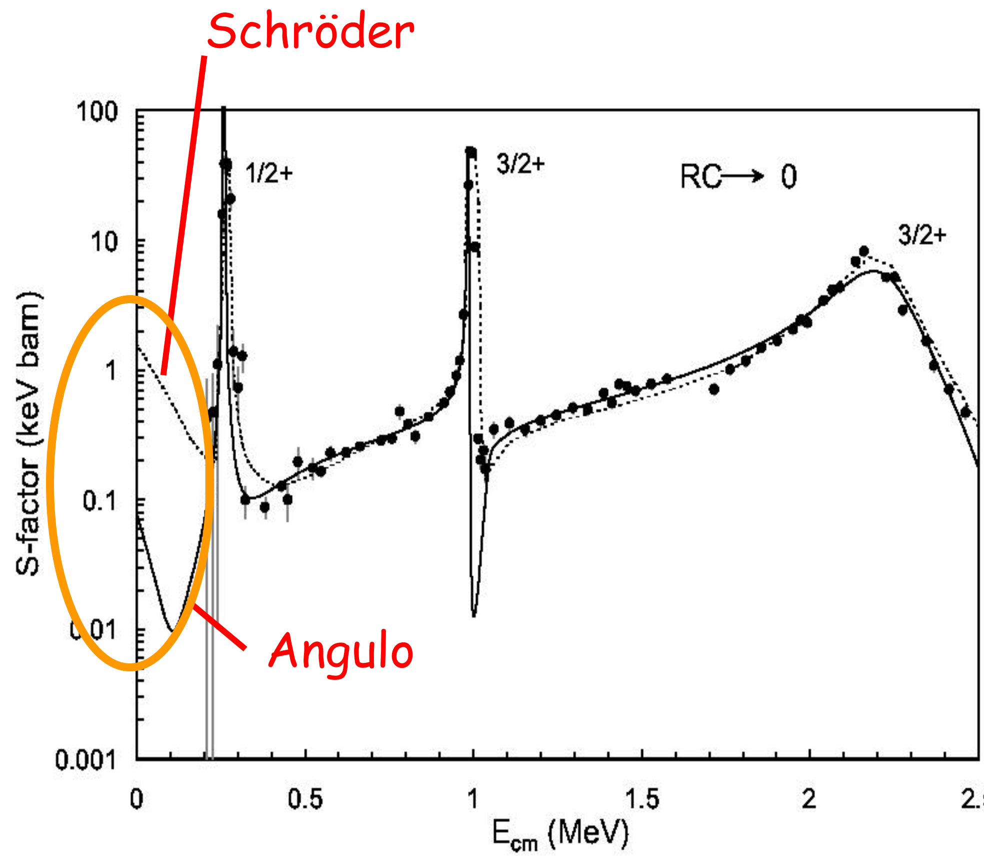
Globular cluster age





$^{14}N(p,\gamma)^{15}O$: the bottleneck of the CNO cycle

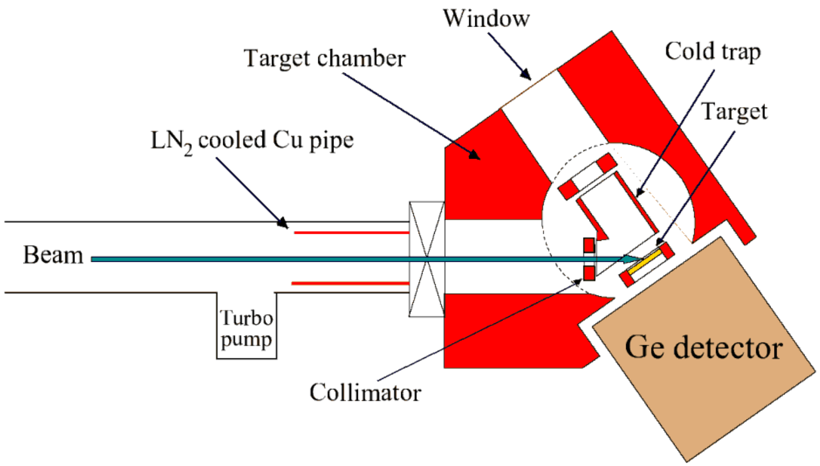




factor 20 !

Transition (MeV)	Schröder et al. (Nucl.Phys.A 1987)	Angulo et al. (Nucl.Phys.A 2001)
RC / 0	1.55 ± 0.34	0.08 ± 0.06
S(0) [kev-b]	3.20 ± 0.54	1.77 ± 0.20

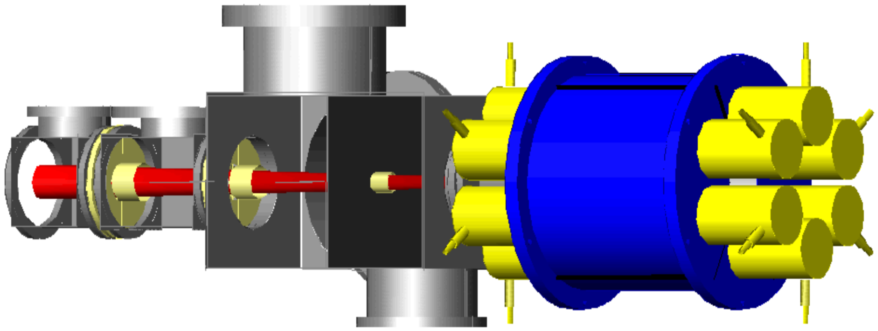
High resolution measurement (2004)



Solid target + HPGe detector

- single γ transitions
- Energy range 119-367 keV
- summing had to be considered

High efficiency measurement (2006)



Gas target+ BGO detector

- high efficiency
- total cross section
- Energy range 70-230 keV

S_0(LUNA) = 1.61 ± 0.08 keV b

CNO neutrino flux decreases of a factor ≈ 2

Globular Cluster age increases of 0.7 – 1 Gyr

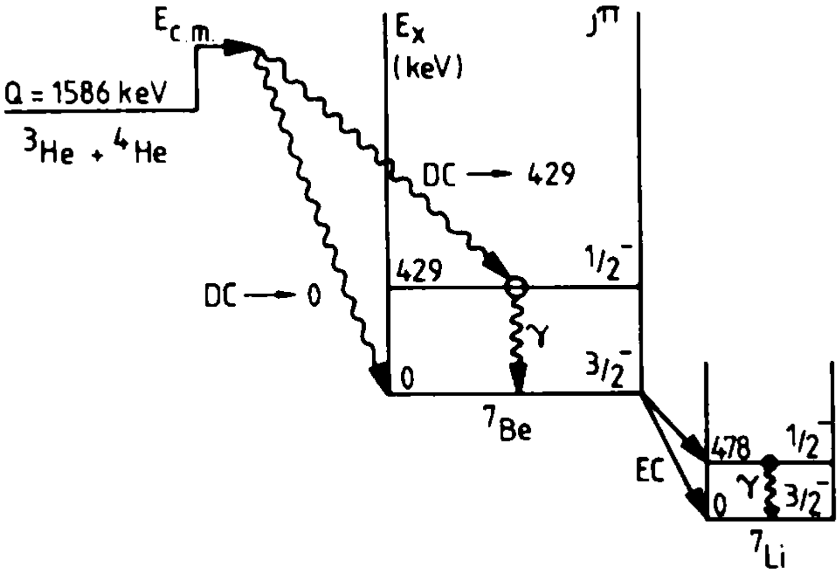
$^3He(^4He,\gamma)^7Be$

John Bahcall e M. H. Pinsonneault, astro-ph/0402114v1, 2004:

The rate of the reaction ^{3}**He(**^{4}**He,**γ**)**^{7}**Be** is the largest nuclear physics contributor to the uncertainties in the solar model predictions of the neutrino fluxes in the p-p chain. In the past 15 years, no one has remeasured this rate; it should be the **highest priority for nuclear astrophysicists**."

$$\Phi(^8B) \sim (1+\delta S_{11})^{-2.73} (1+\delta S_{33})^{-0.43} (1+\delta S_{34})^{0.85} (1+\delta S_{17})^{1.0} (1+\delta S_{e7})^{-1.0} (1+\delta S_{1,14})^{-0.02}$$

where fractional uncertainty $\delta S_{11} \equiv \Delta S_{11}/S_{11}(0)$



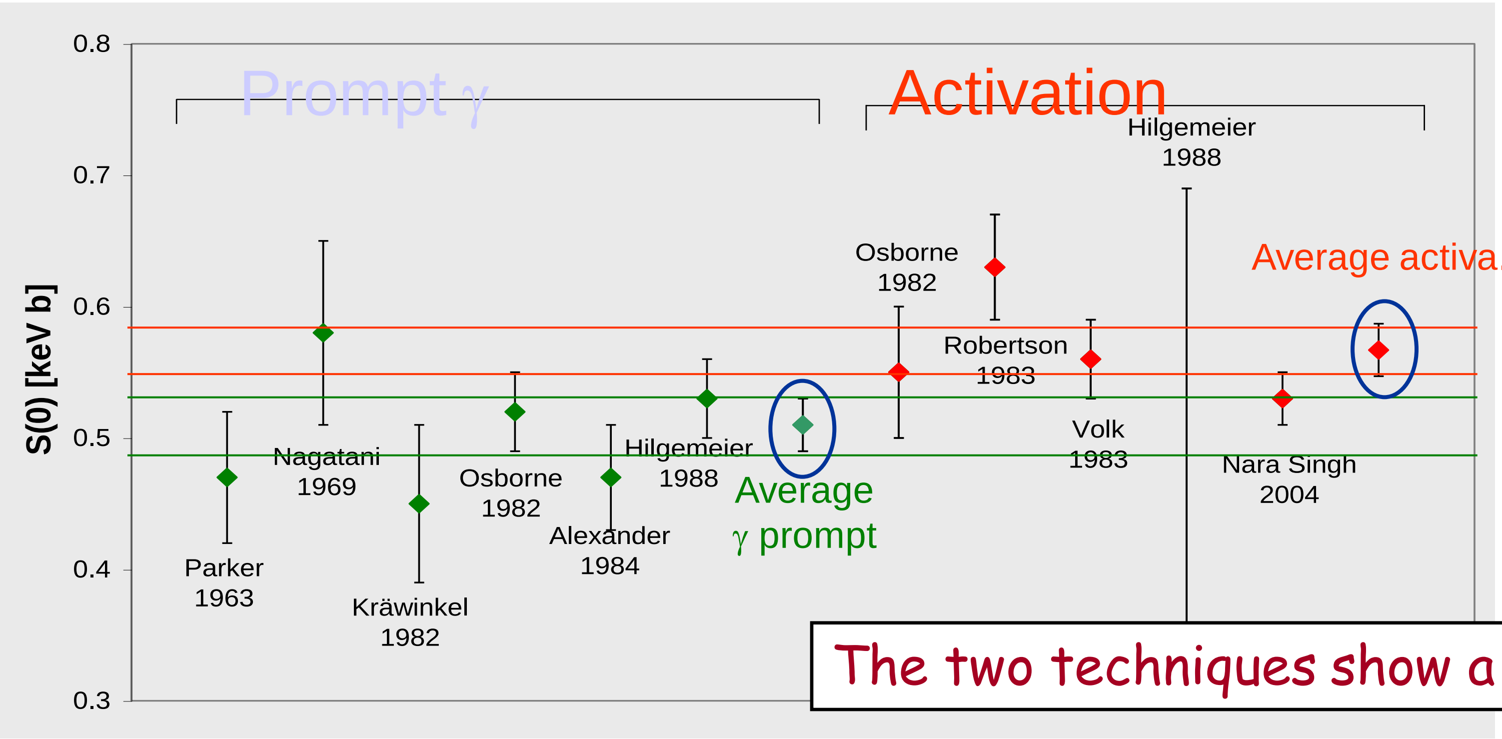
$^3He(\alpha,\gamma)^7Be(e,\nu)\ ^7Li^*(\gamma)^7Li$

$E\gamma = 478$ keV

$E\gamma = 1586$ keV + E_{cm} (DC → 0);

$E\gamma = 1157$ keV + E_{cm} (DC → 429)

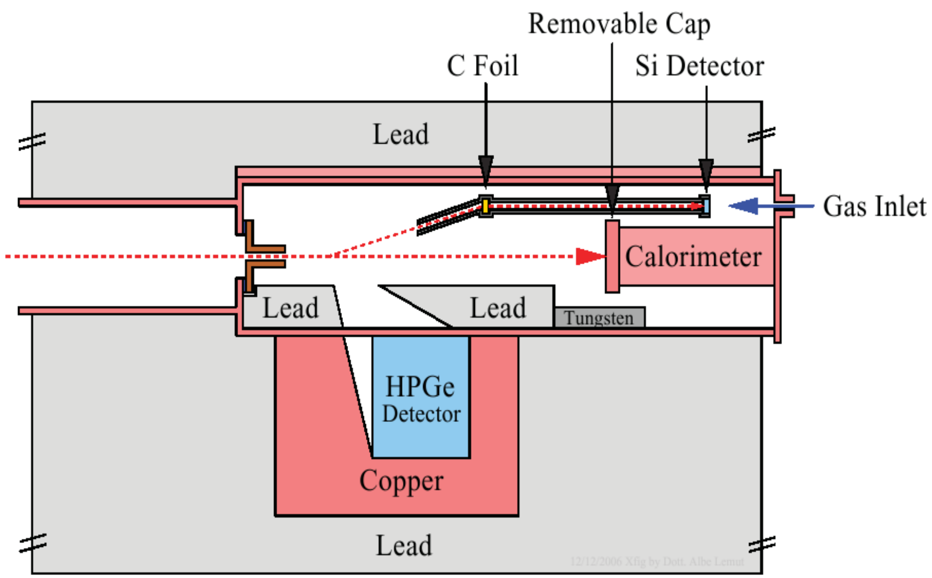
$E\gamma = 429$ keV



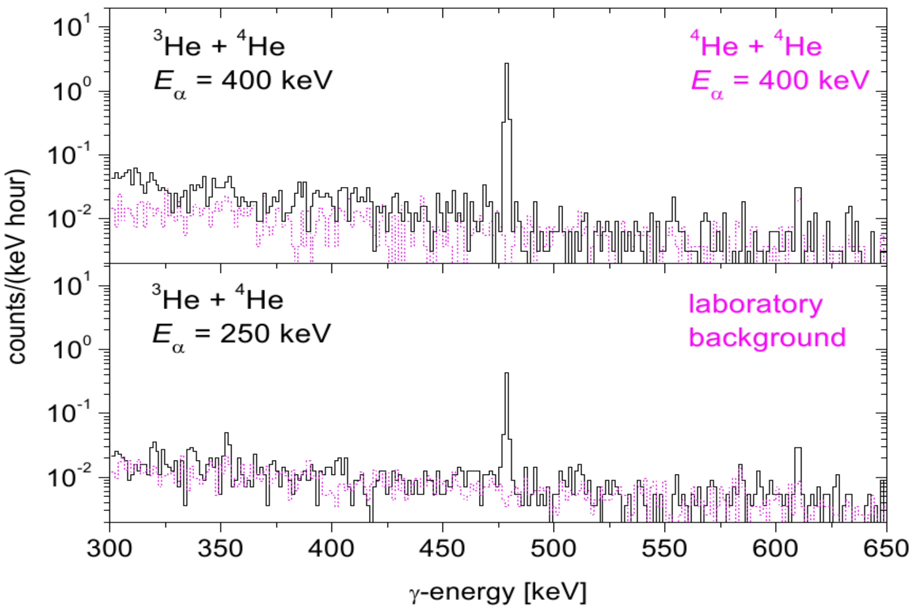
The two techniques show a 9% discrepancy

Luna measurement: both techniques and accuracy of 4-5%

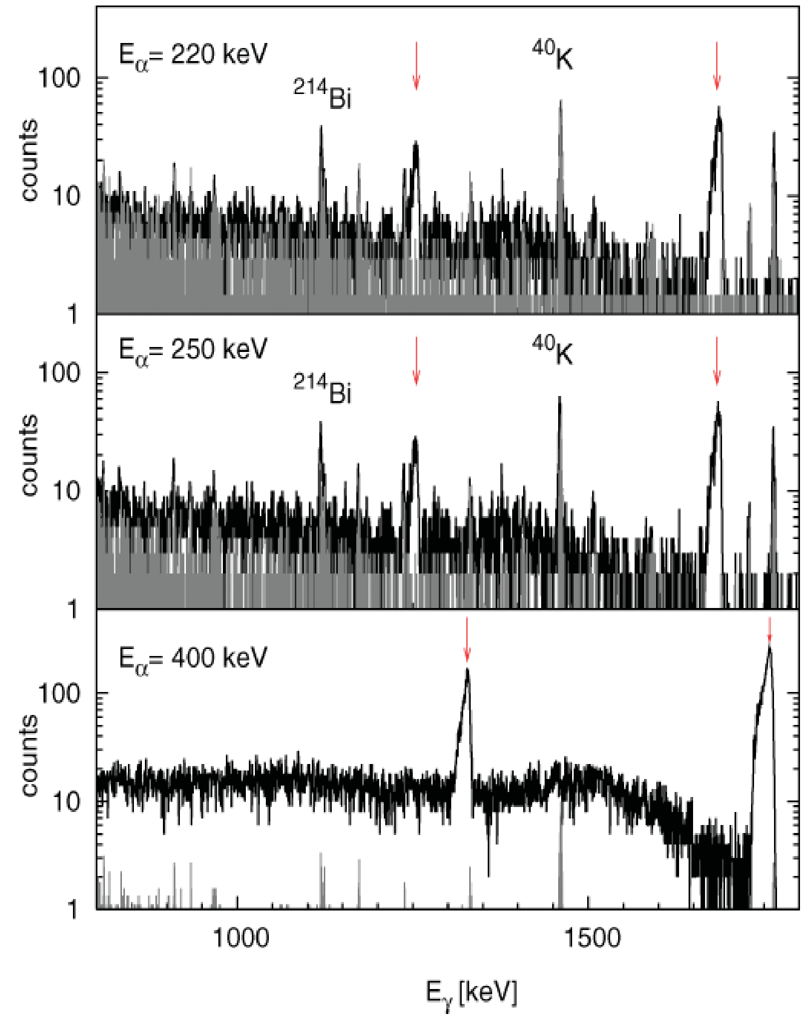
- ^{3}He recirculating gas target p=0.7mbar
- Si-monitor for target density measurement (beam heating effect)
- Collimated HPGe detector to collect γ ray at 55°
- 0.3 m^3 Pb-Cu shield suppression five orders of magnitude below 2MeV
- Removable calorimeter cap for offline ^{7}Be counting



Spectra

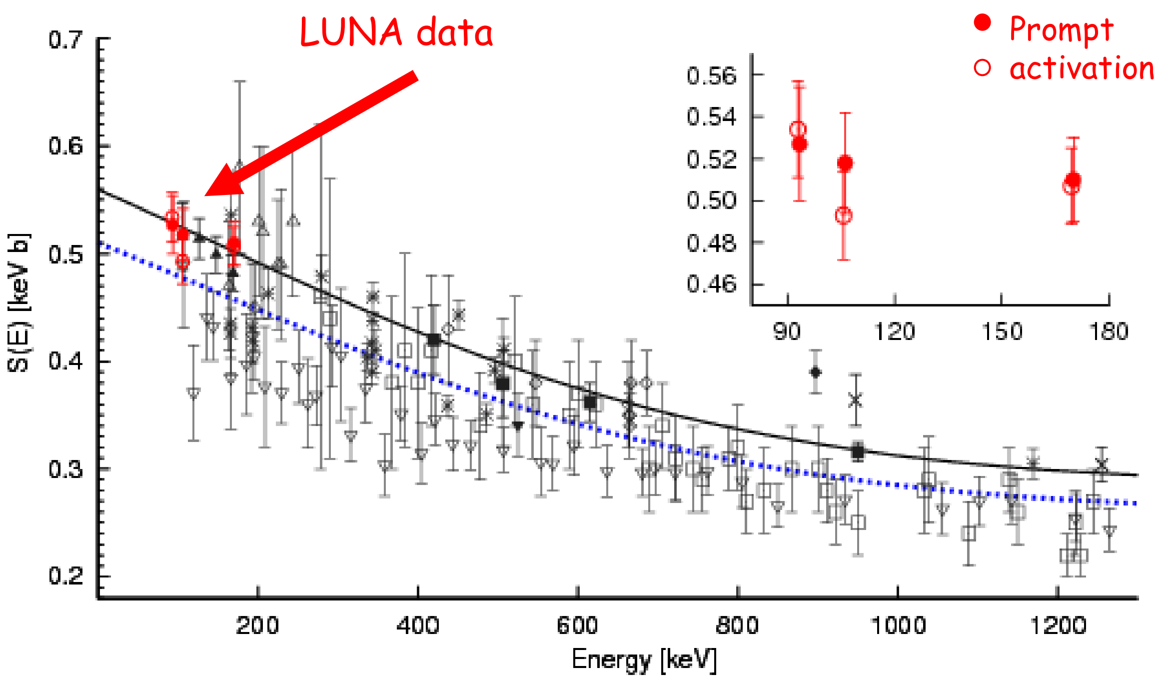


Activation



Prompt

Results

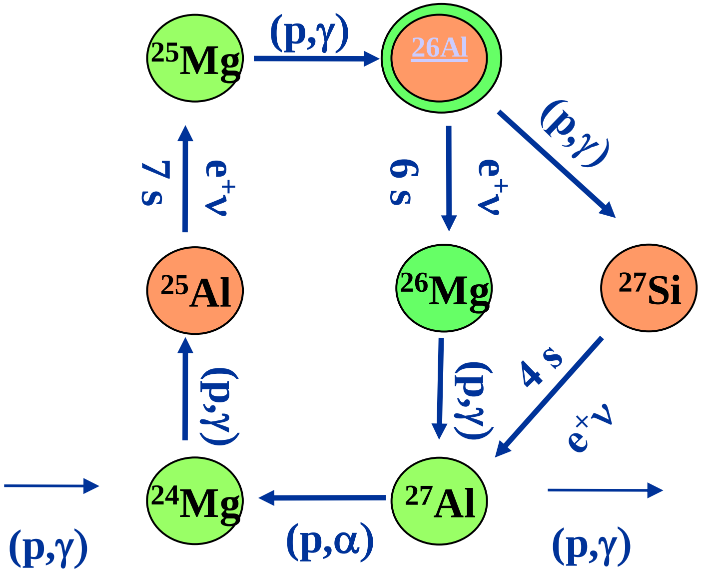


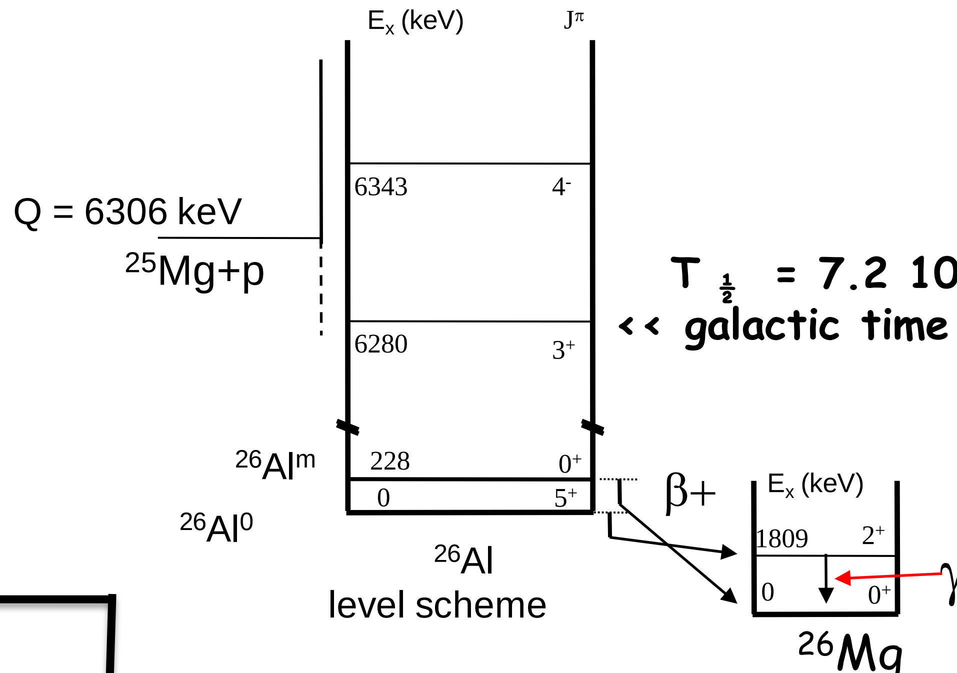
S_{34} (LUNA) =0.567±0.018±0.004 keV b

in Solar fusion cross sections II: arXiv:1004.2318v3
based on LUNA and successive measurements:
S_{34}= 0.56 ± 0.02 (exp) ± 0.02 (model) keV b

Uncertainty due to S_{34} on neutrinos flux:
$\Phi(^8B)$ 7.5% → 4.3%
$\Phi(^7Be)$ 8% → 4.5%

$^{25}Mg(p,\gamma)^{26}Al$

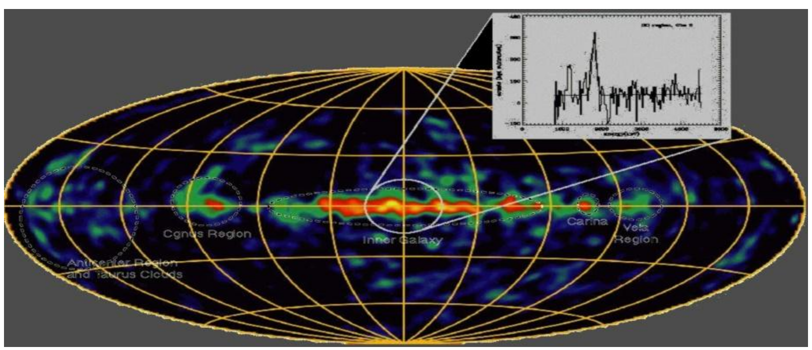




$T_{\frac{1}{2}} = 7.2\ 10^5$ y

<< galactic time scale

1.8 MeV ^{26}Al decay γ-ray line

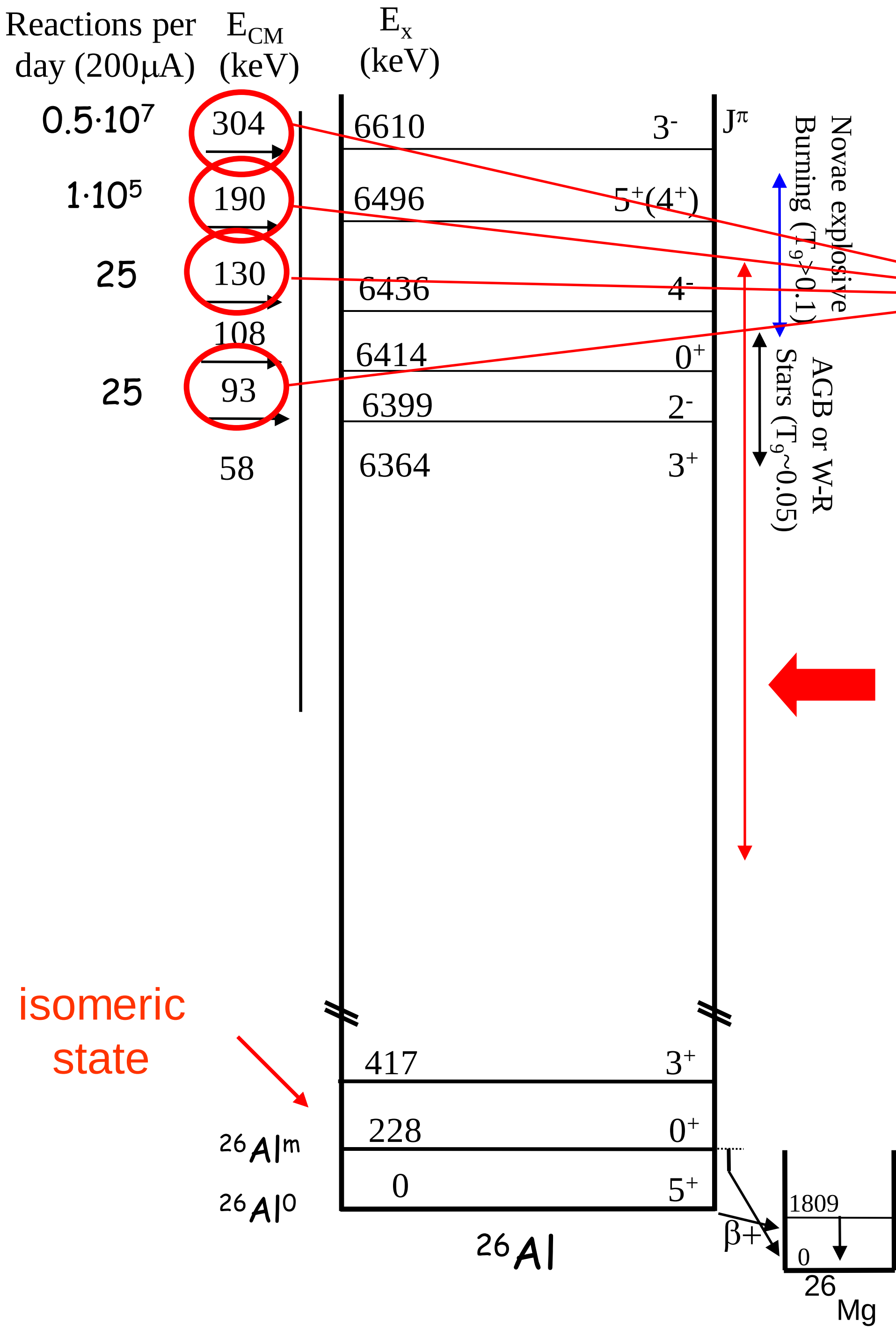


^{26}Mg excess in meteorite

Evidence that ^{26}Al nucleosynthesis is still active (SN and NOVAE)

^{26}Al produced before the formation of the solar system

$^{25}Mg(p,\gamma)^{26}Al$

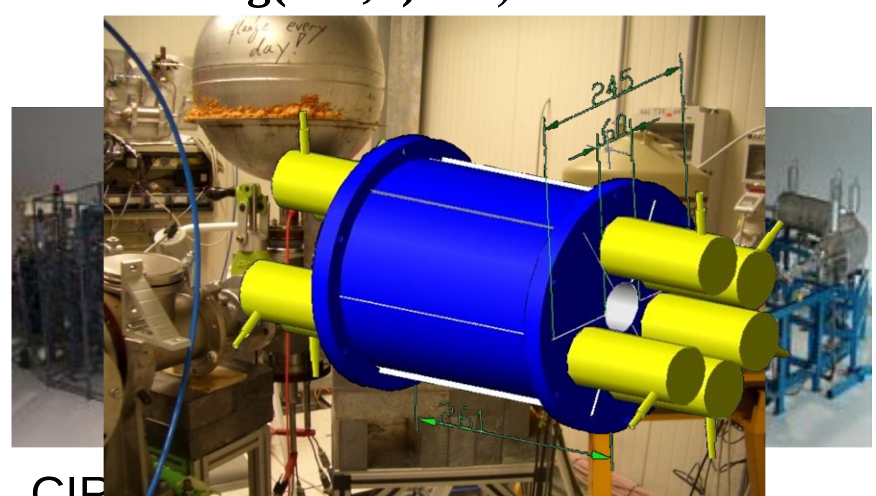


γ-ray Spectroscopy with HPGe
High resolution & Low efficiency
(≤1% @ high energy) +
solid target @55°

AMS: Irradiation & Measurement
→ (resonance strength ωγ)

γ-ray Spectroscopy with 4πBGO
+ solid target
→ High efficiency (> 60%) – Low
resolution set-up

No direct strength resonance data
(level structure derived from the single particle transfer reaction: **$^{25}Mg(^3He,d)^{26}Al$**)



CIR... lab. Caserta, Italy

Precise measurement of a resonance →
accurate evaluation of the target stoichiometry
Enriched targets may contain oxygen
Study of "high" energy resonances with natural and enriched Mg targets of :

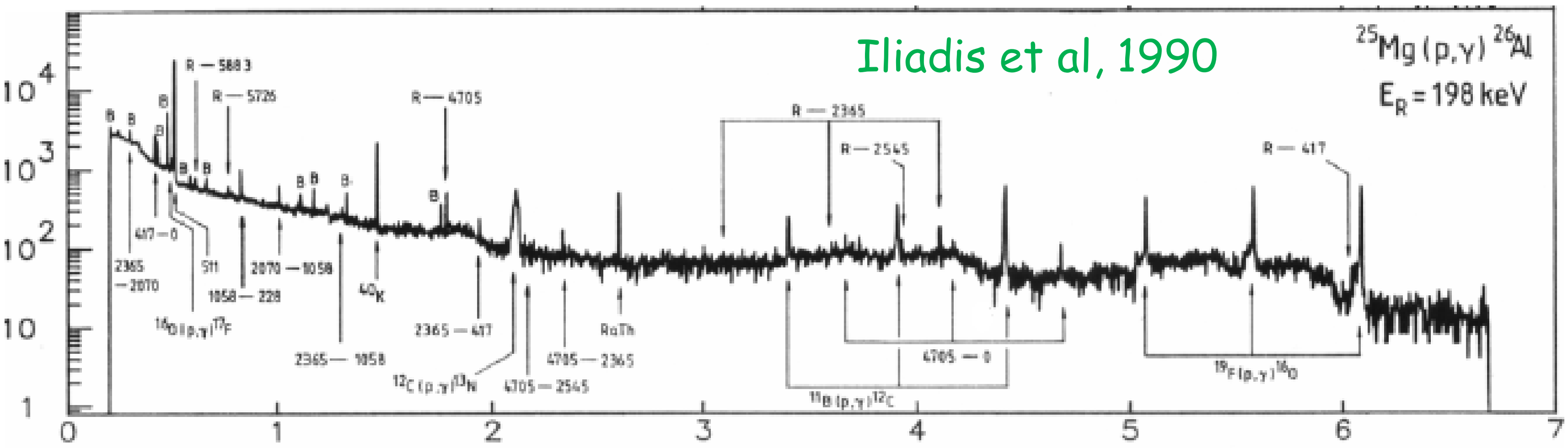
$^{25}Mg(p,\gamma)^{26}Al$ (E_r=304 keV): Confirmed NACRE result but reduced uncertainty to 4%. This resonance will serve as normalization standard for lower-energy resonances

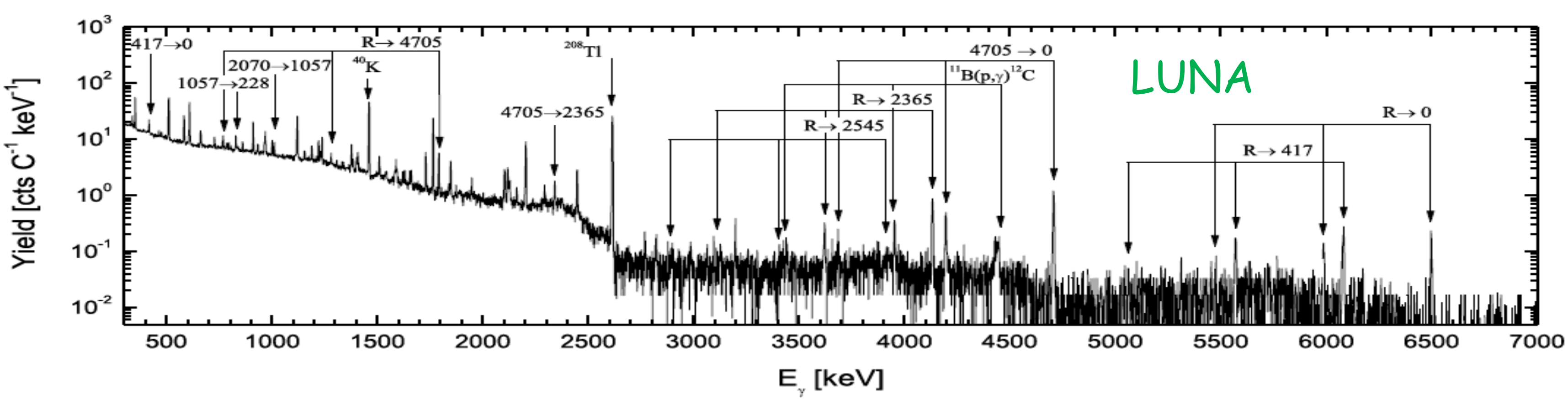
$^{24}Mg(p,\gamma)^{25}Al$ (E_r=214 keV): lower resonance strength with respect to previous literature data. Strong direct capture component. Need of a re-analysis with R-matrix

$^{26}Mg(p,\gamma)^{27}Al$ (E_r=326 keV): apparent discrepancy in literature data solved. Resonance strength measured with higher accuracy

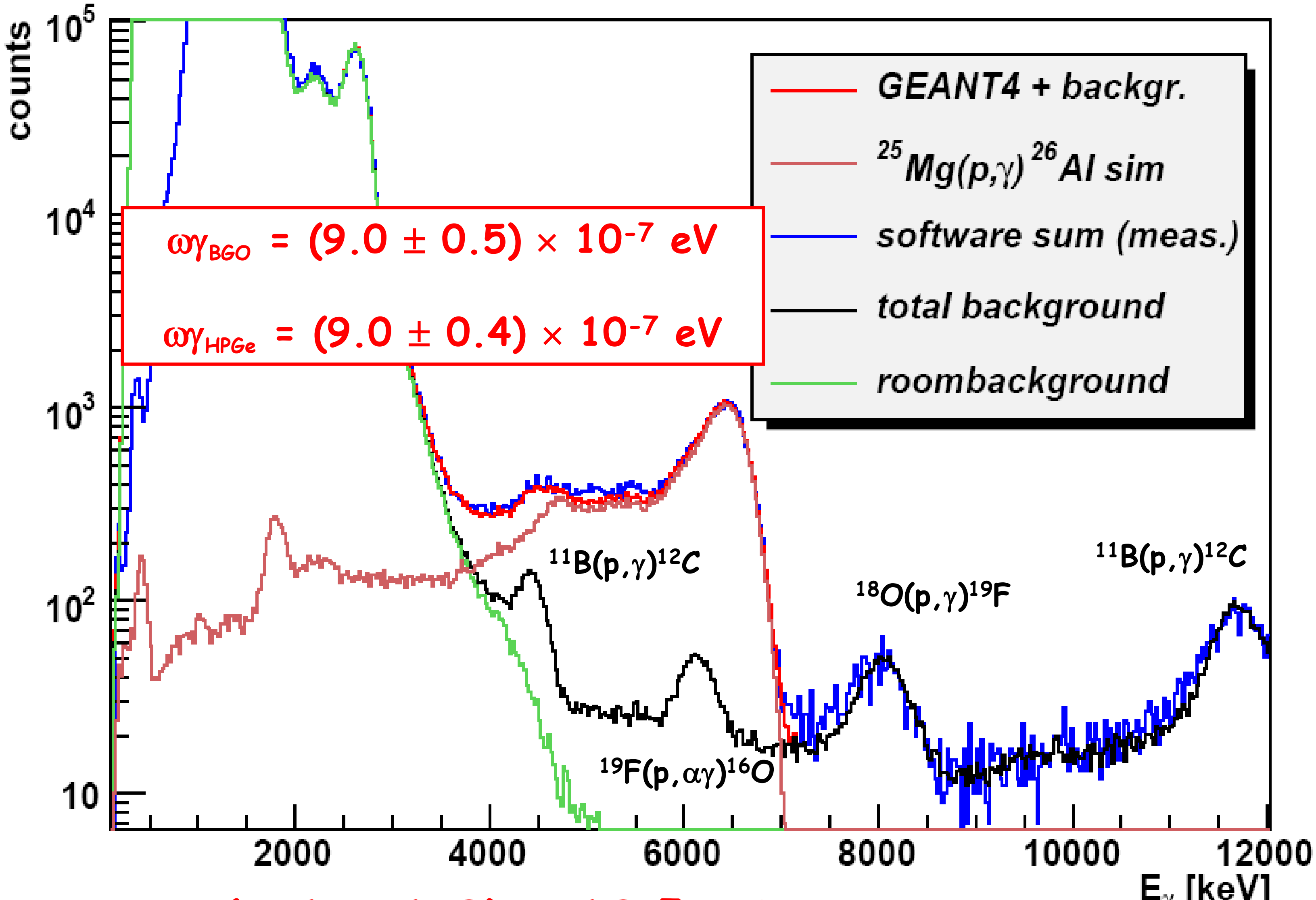
$^{25}Mg(p,\gamma)^{26}Al$

198 keV resonance HPGe γ-ray spectra: single transitions



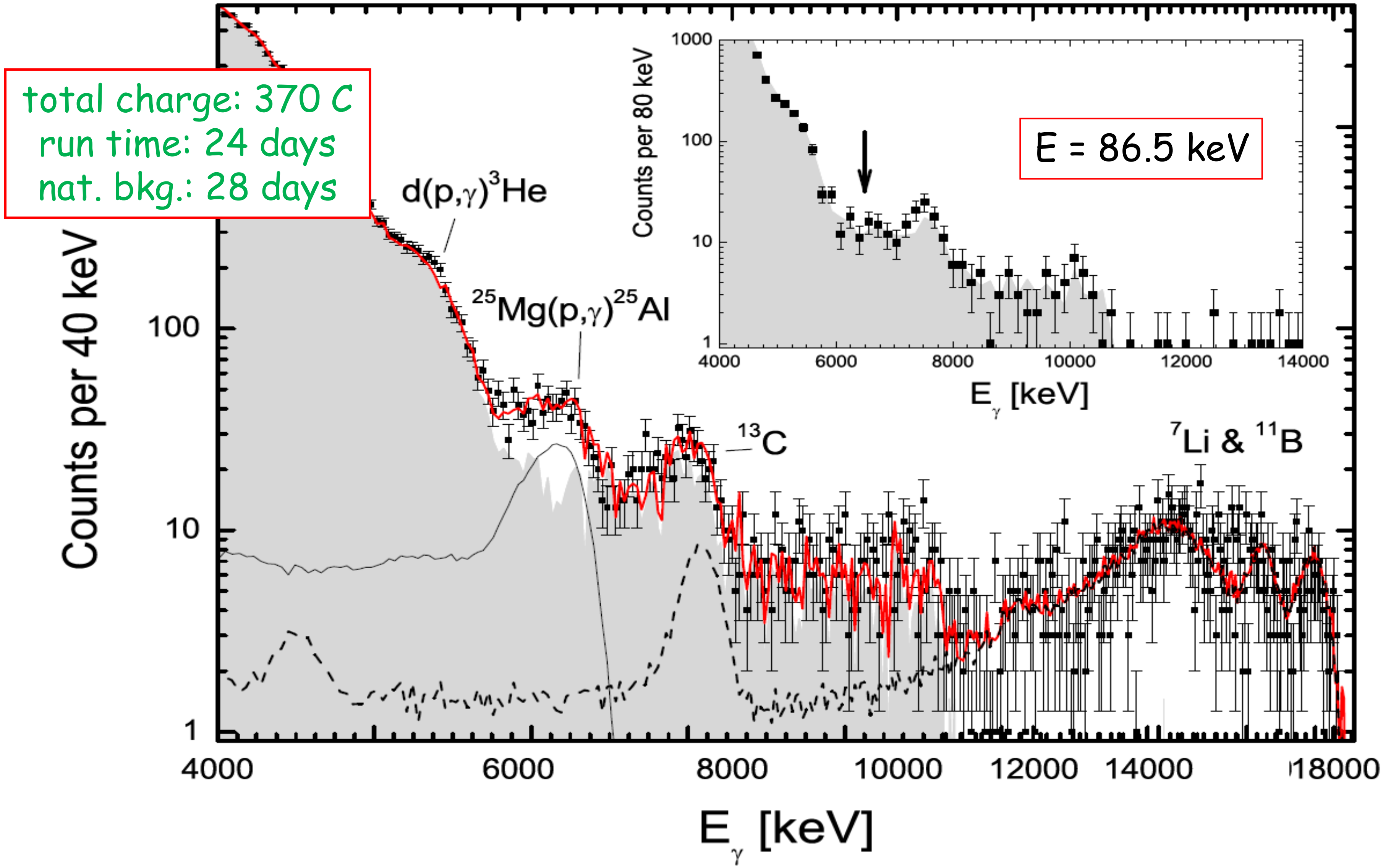


198 keV resonance BGO γ-ray spectra



$\omega\gamma_{NACRE} = (7.1 \pm 1.0) \times 10^{-7}$ eV

92 keV resonance BGO γ-ray spectra



$\omega\gamma_{92} = (2.9 \pm 0.6) \times 10^{-10}$ eV

$\omega\gamma_{92}^{\rm NACRE} = (1.16^{+1.16}_{-0.39}) \times 10^{-10}$ eV (indirect)

LUNA present program

completed!

CNO cycle

In progress
(D. Scott talk)

Ne-Na cycle

BBN

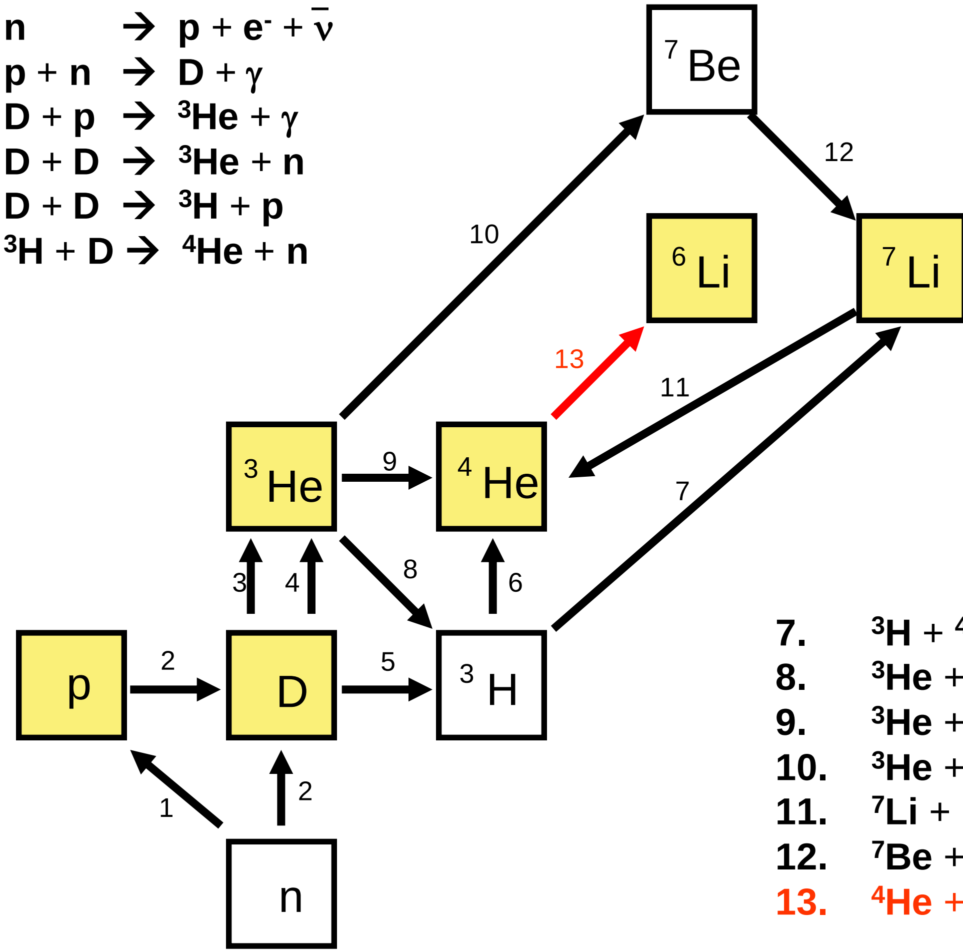
In progress

reaction	Q-value (MeV)	Gamow energy (keV)	Lowest meas. Energy (keV)	LUNA limit
$^{15}N(p,\gamma)^{16}O$	12.13	10-300	130	50
$^{17}O(p,\gamma)^{18}F$	5.6	35-260	300	65
$^{18}O(p,\gamma)^{19}F$	8.0	50-200	143	89
$^{23}Na(p,\gamma)^{24}Mg$	11.7	100-200	240	138
$^{22}Ne(p,\gamma)^{23}Na$	8.8	50-300	250	68
$D(\alpha,\gamma)^{6}Li$	1.47	50-300	700(direct) 50(indirect)	50

to be completed presumably by 2014

BBN: production of the lightest elements (D, ^{3}He, ^{4}He, ^{7}Li, ^{6}Li) in the first minutes after the Big Bang

1. n → p + e^- + $\bar{\nu}$
2. p + n → D + γ
3. D + p → ^{3}He + γ
4. D + D → ^{3}He + n
5. D + D → ^{3}H + p
6. ^{3}H + D → ^{4}He + n

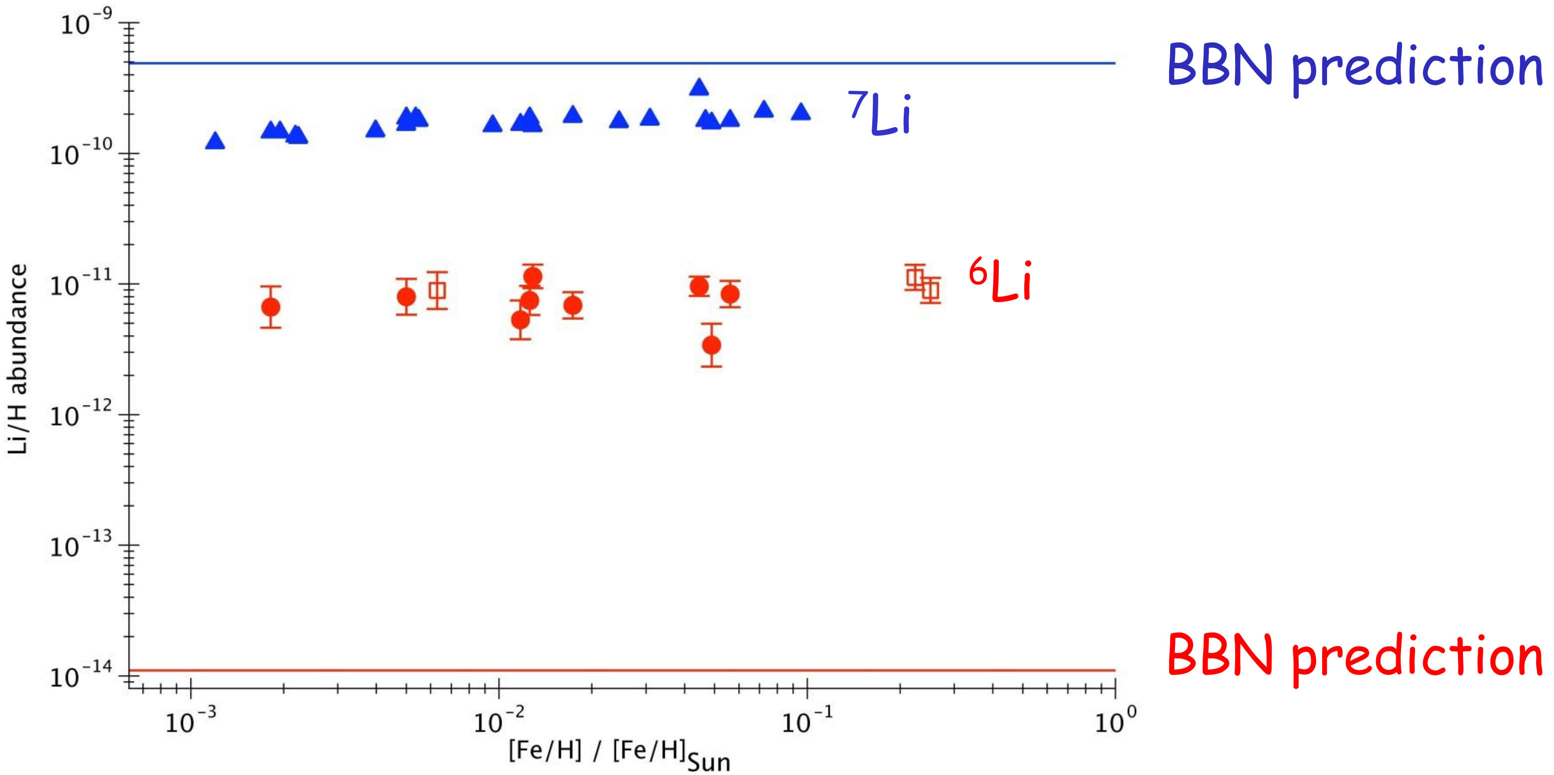


7. ^{3}H + ^{4}H → ^{7}Li + γ
8. ^{3}He + n → ^{3}H + p
9. ^{3}He + D → ^{4}He + p
10. ^{3}He + ^{4}He → ^{7}Be + γ
11. ^{7}Li + p → ^{4}He + ^{4}He
12. ^{7}Be + n → ^{7}Li + p
13. ^{4}He + D → ^{6}Li + γ

Apart from ^{4}He, uncertainties are dominated by systematic errors in the nuclear cross sections

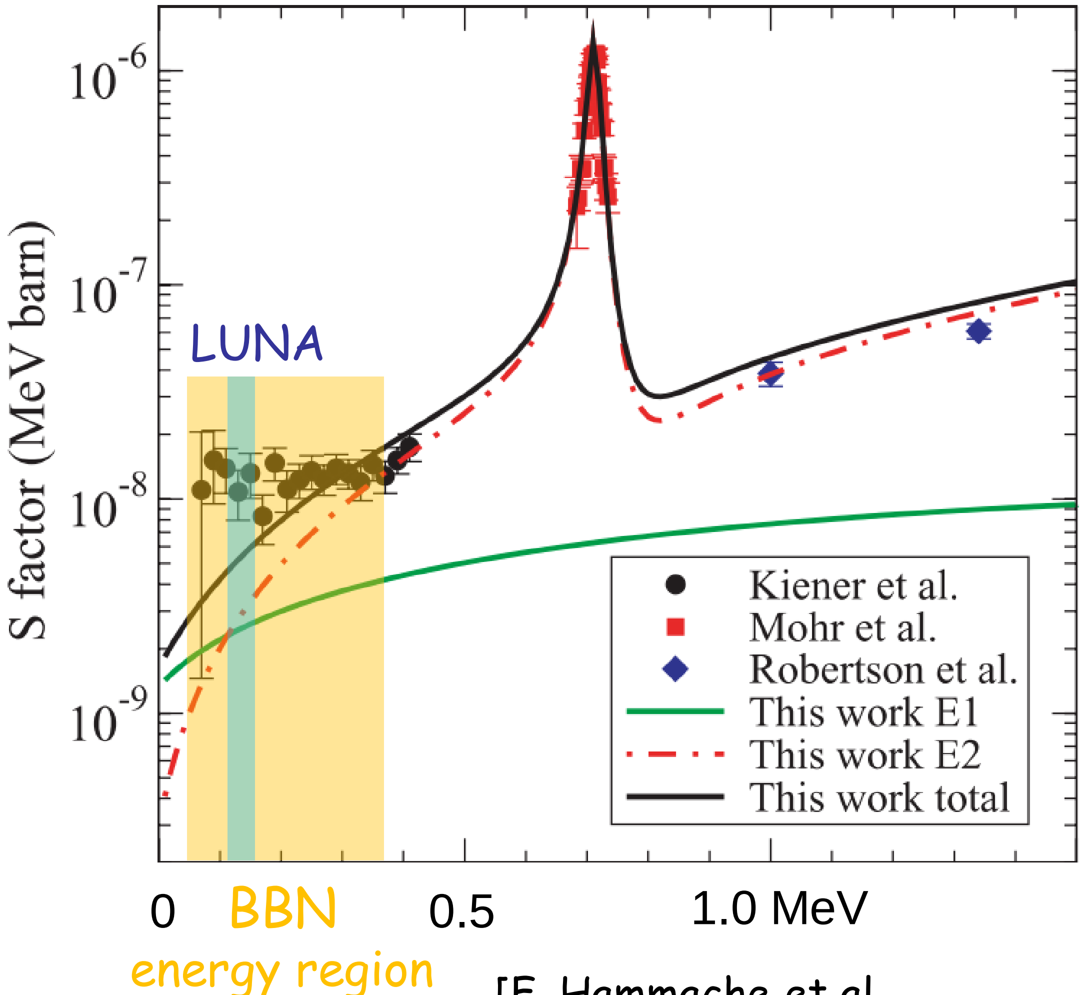
The ^{6}Li case

Constant amount in stars of different metallicity (→age)
2-3 orders of magnitude higher than predicted with the BBN network (NACRE)



The primordial abundance is determined by:
^{2}H(α,γ)^{6}Li producing almost all the ^{6}Li
^{6}Li(p,α)^{3}He destroying ^{6}Li → well known

Available data



Direct measurements:
- Robertson et al.
E > 1 MeV
- Mohr et al.
around the 0.7 MeV resonance

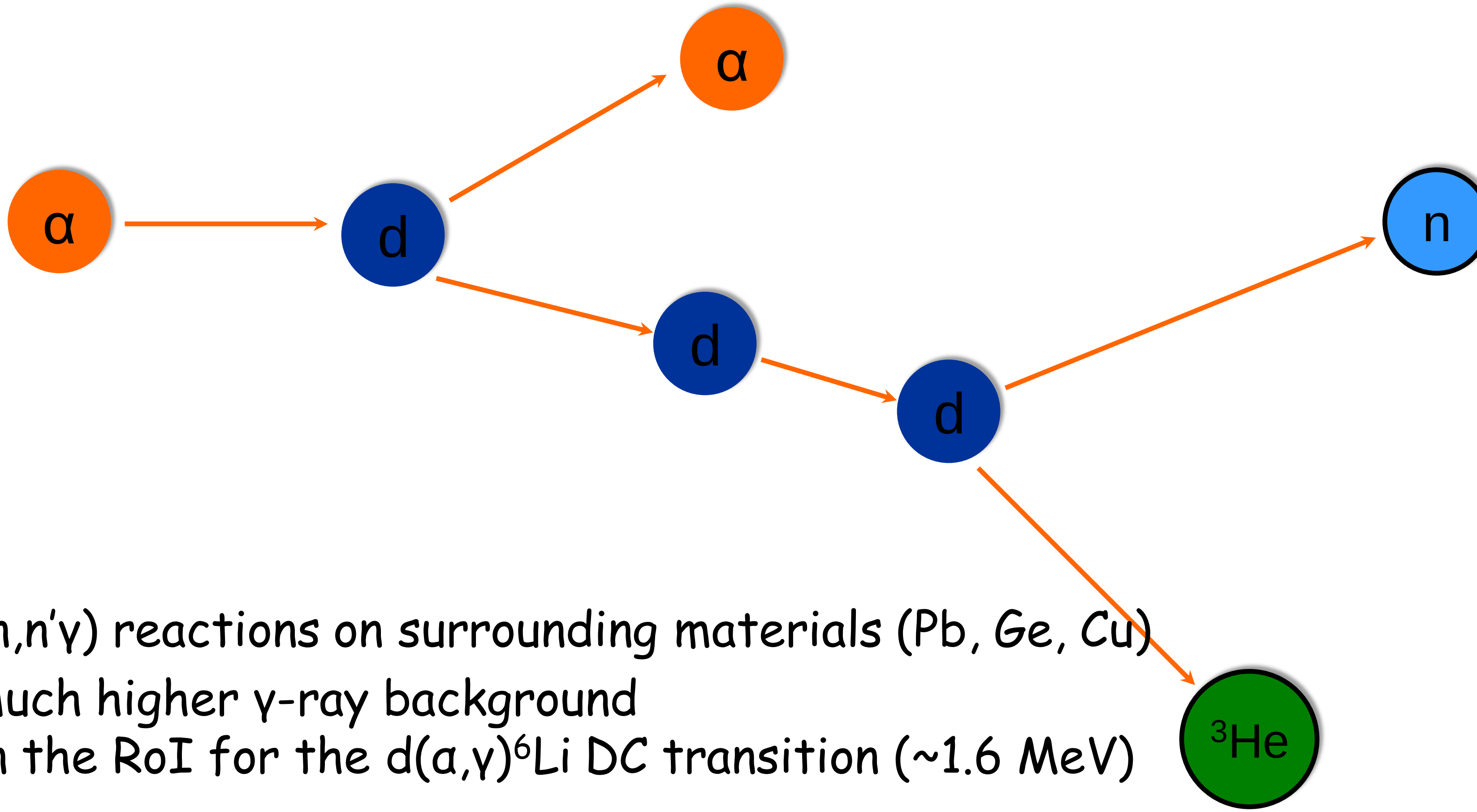
Indirect measurements:
- Hammache et al.
upper limits with high energy Coulomb break-up

At LUNA direct measurements at the energies of astrophysical interest

[F. Hammache et al., Phys. Rev. C 82, 065803 (2010)]

The beam-induced background

- neutron background generated by $d(\alpha,\alpha)d$ Rutherford scattering followed by $d(d,n)^3He$ reactions



-> (n,n′γ) reactions on surrounding materials (Pb, Ge, Cu)

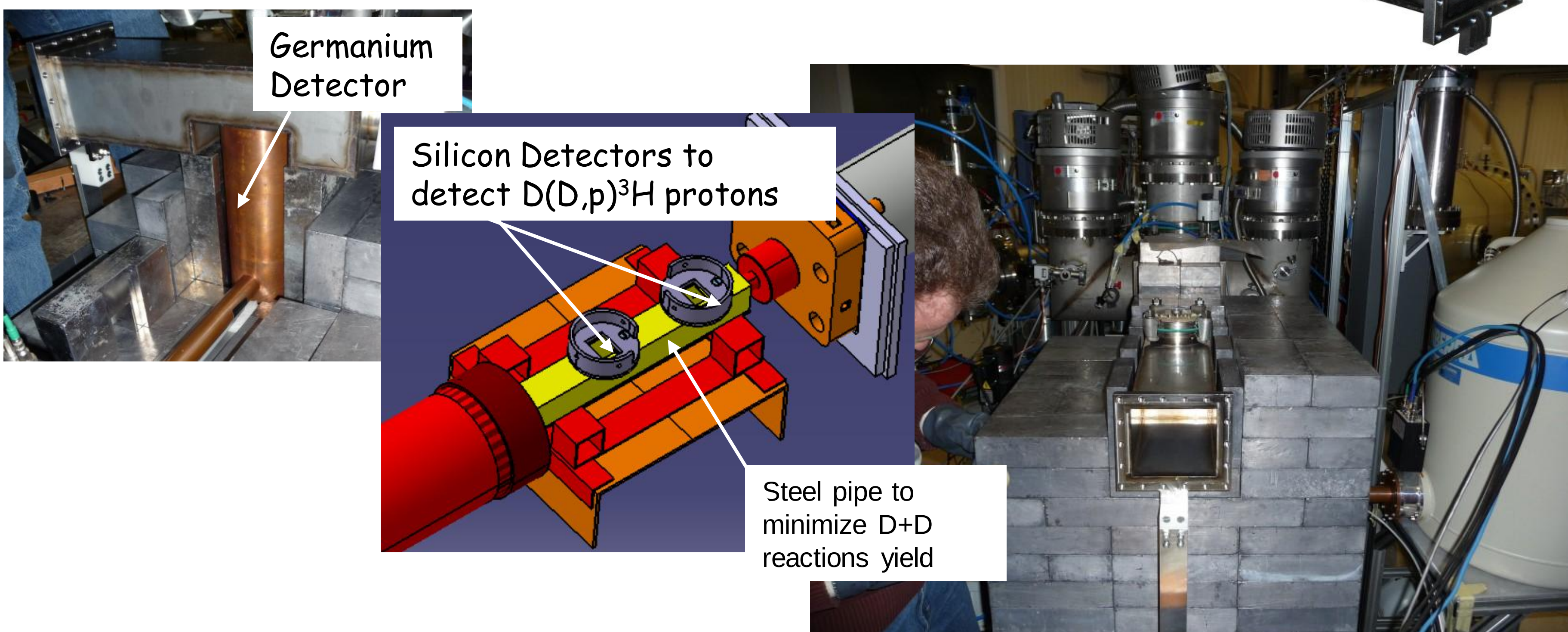
-> much higher γ-ray background in the RoI for the $d(\alpha,\gamma)^6Li$ DC transition (~1.6 MeV)

Experimental set-up

Reduced gas volume: pipe to minimize the path of scattered ^{2}H and hence to minimize the d(d,n)^{3}He reaction yield

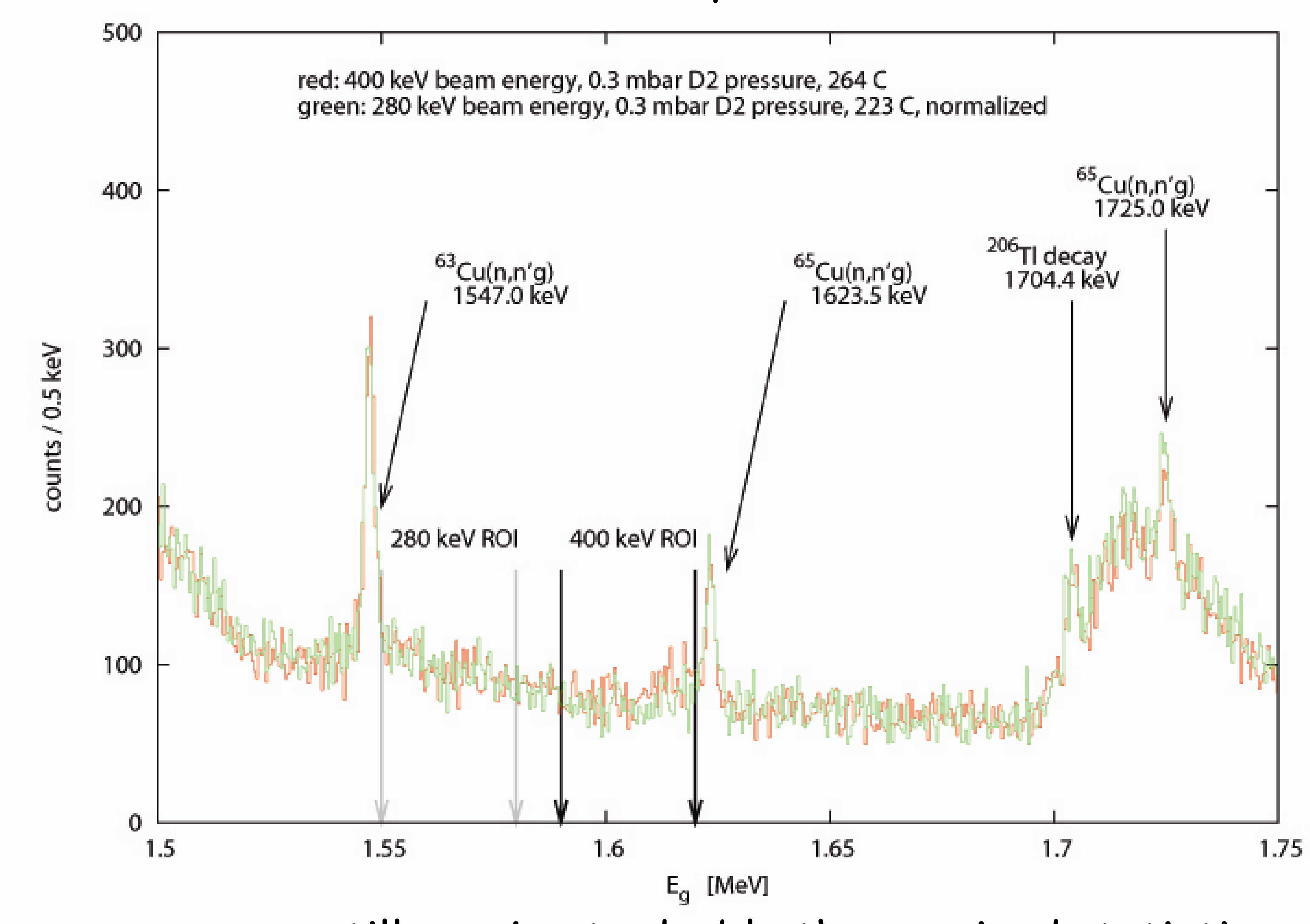
- HPGe detector in close geometry: larger detection efficiency and improved sygnal-to-noise ratio

- Silicon detectors to measure ^{2}H(^{2}H,p)^{3}H



LUNA measurement (preliminary)

230 h at 400 keV, 285 h at 280 keV



still running to double the acquired statistics

LUNA MV Project

April 2007: a Letter of Intent (LoI) was presented to the LNGS Scientific Committee (SC) containing key reactions of the He burning and neutron sources for the s-process:

$^{12}C(\alpha,\gamma)^{16}O$

$^{13}C(\alpha,n)^{16}O$

$^{22}Ne(\alpha,n)^{25}Mg$

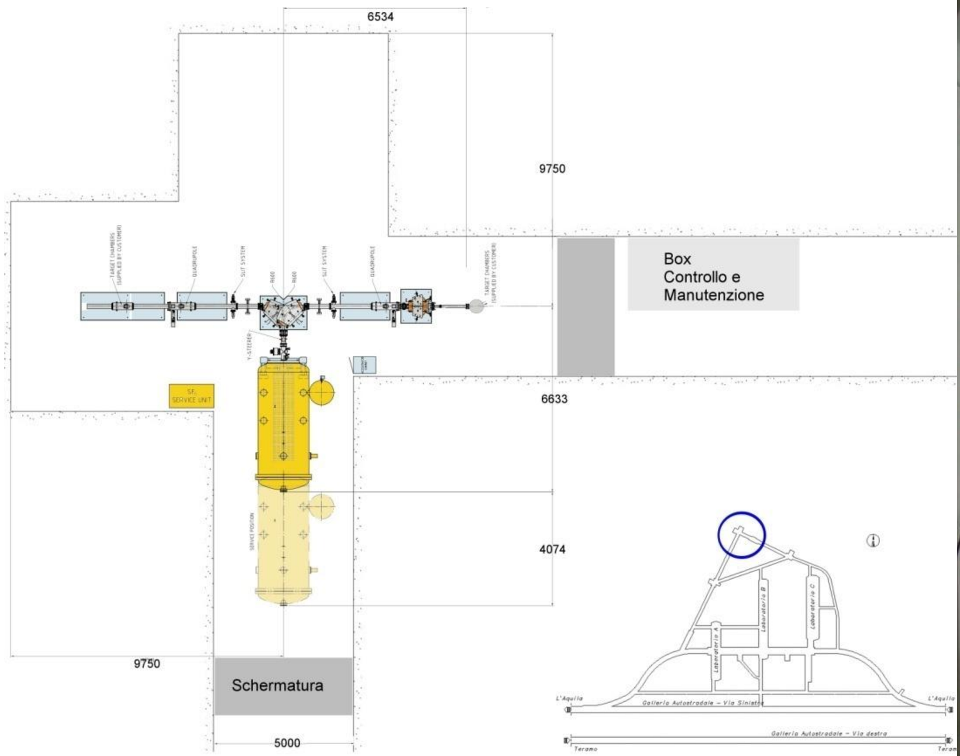
(α,γ) reactions on $^{14,15}N$ and ^{18}O

These reactions are relevant at higher temperatures (larger energies) than reactions belonging to the hydrogen-burning studied so far at LUNA

↓

Higher energy machine→ 3.5 MV single ended positive ion accelerator

Possible location at the "B node" of a 3.5 MV single-ended positive ion accelerator



- In a very low background environment such as LNGS, it is mandatory not to increase the neutron flux above its average value

$^{13}C(\alpha,n)^{16}O$

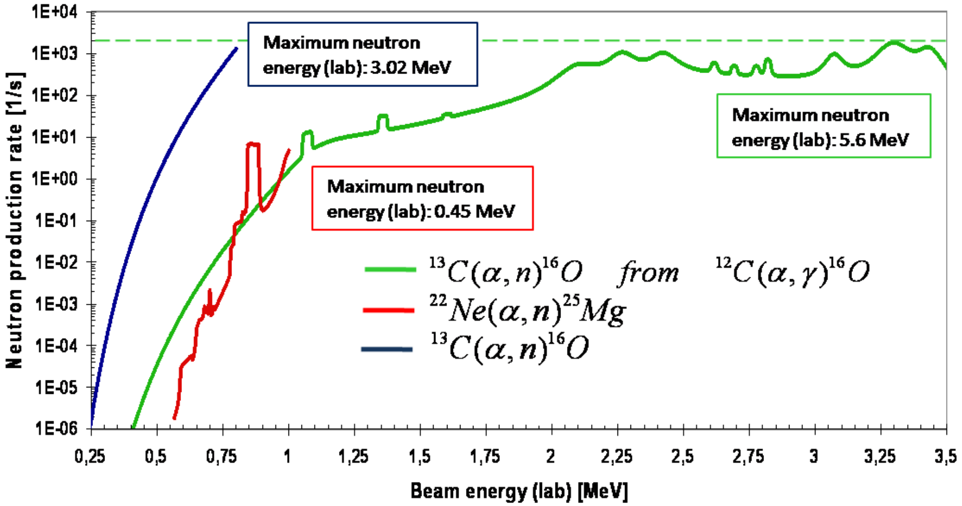
α beam intensity: 200 μA
Target: ^{13}C, 2 10^{17}at/cm^2 (99% ^{13}C enriched)
Beam energy(lab) ≤ 0.8 MeV

$^{22}Ne(\alpha,n)^{25}Mg$

α beam intensity: 200 μA
Target: ^{22}Ne, 1 10^{18}at/cm^2
Beam energy(lab) ≤ 1.0 MeV

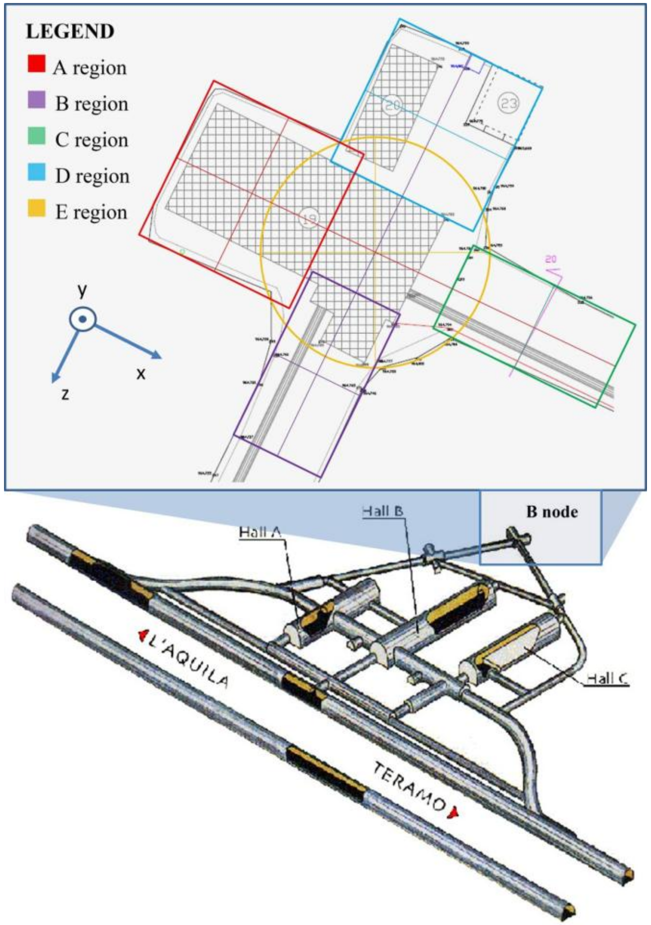
$^{13}C(\alpha,n)^{16}O$ from $^{12}C(\alpha,\gamma)^{16}O$

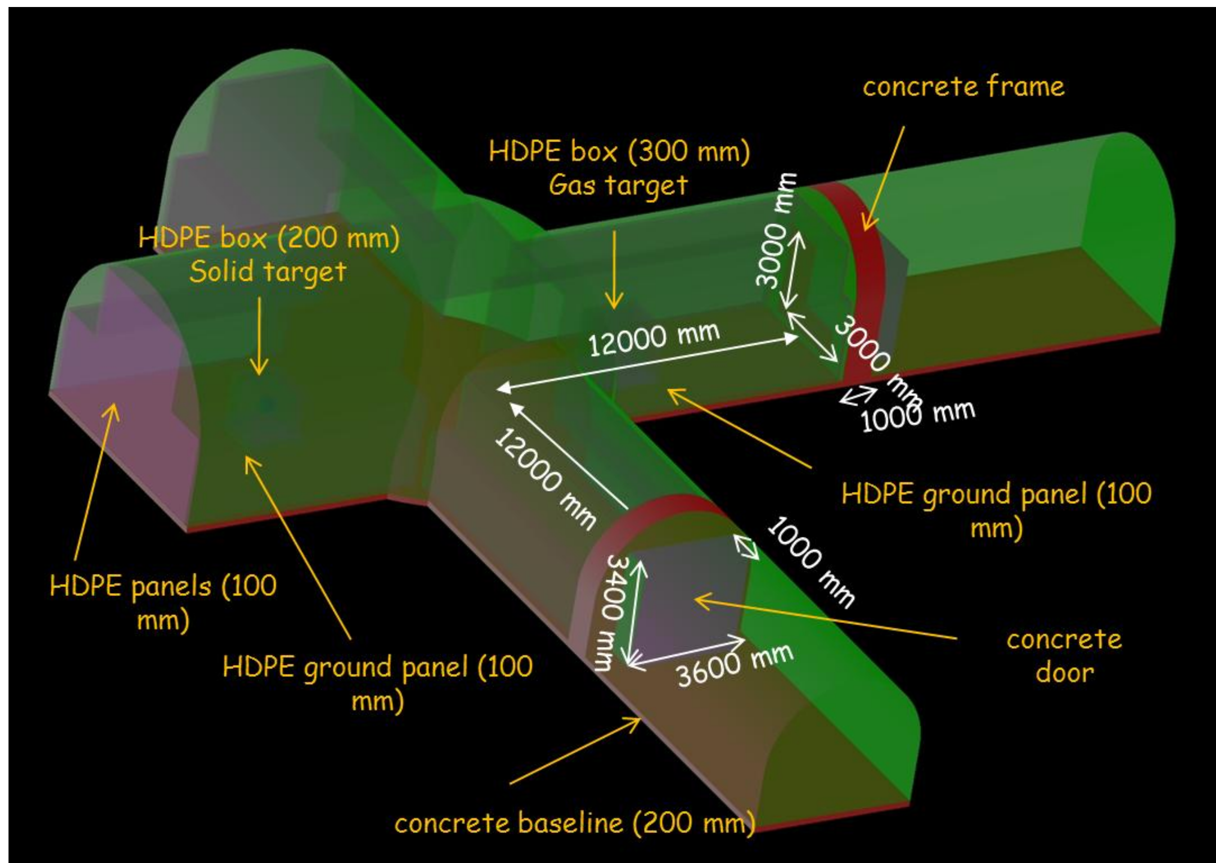
α beam intensity: 200 μA
Target: ^{13}C, 1 10^{18}at/cm^2 ($^{13}C/^{12}C = 10^{-5}$)
Beam energy(lab) ≤ 3.5 MeV



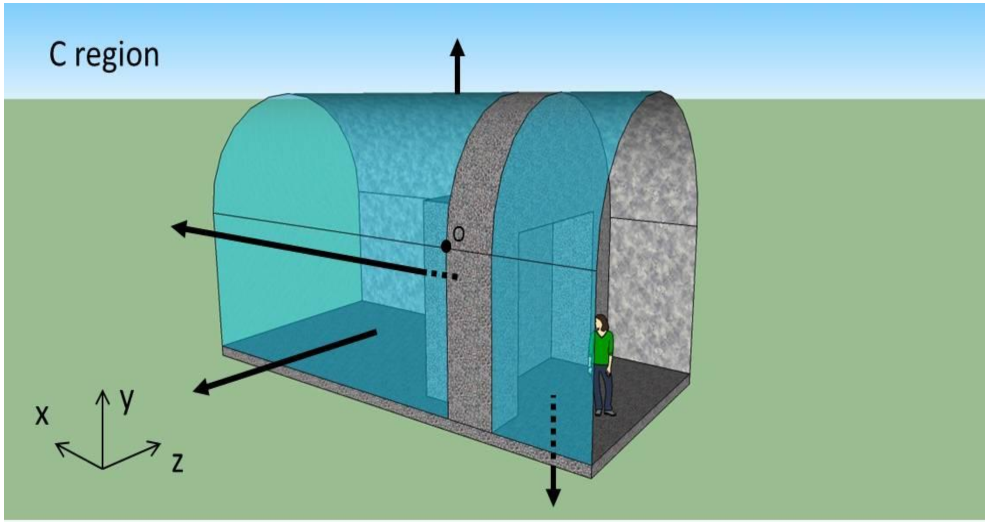
- Maximum neutron production rate : 2000 n/s
- Maximum neutron energy (lab) : 5.6 MeV

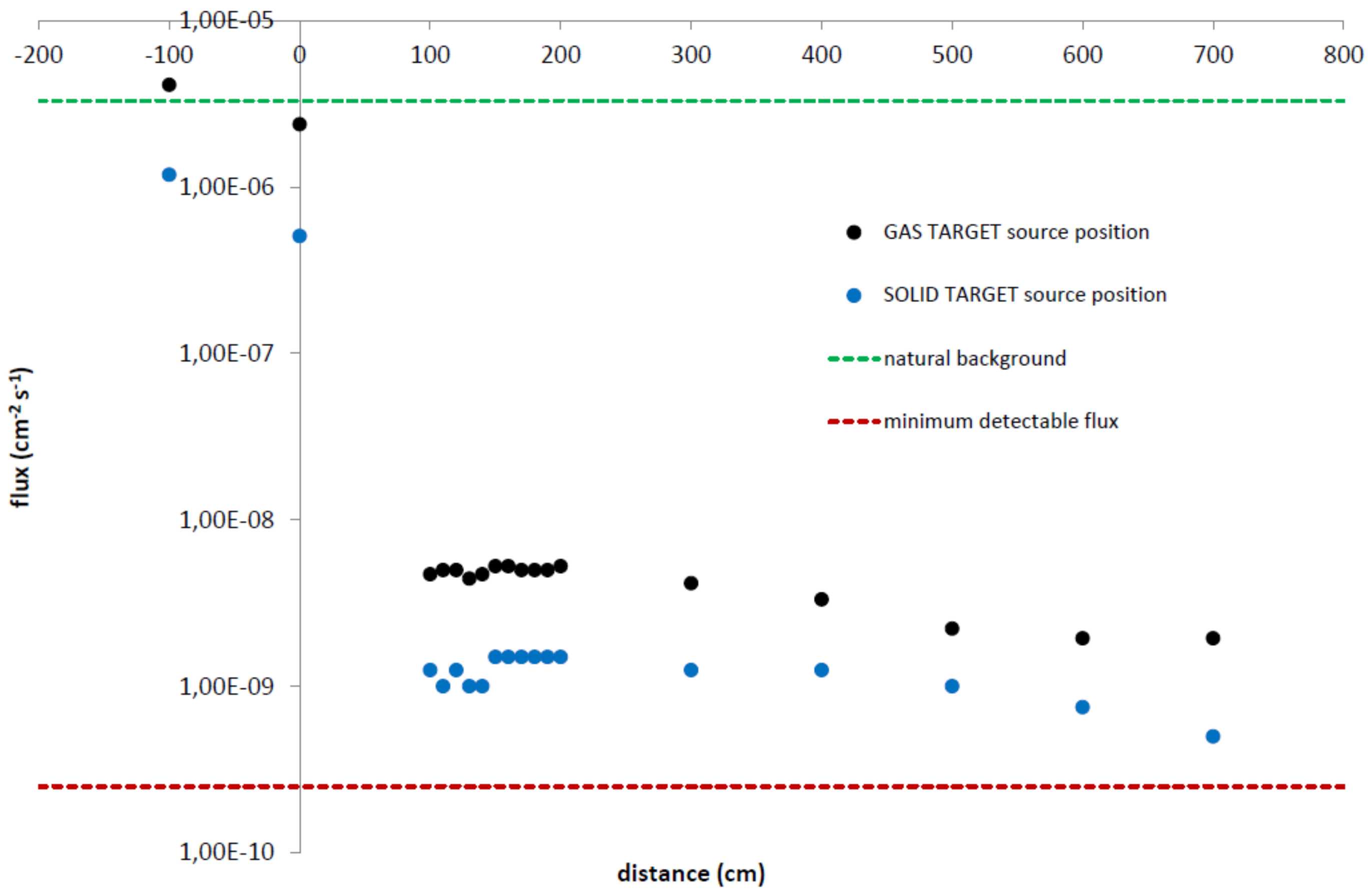
Geant4 simulations for neutron fluxes just outside the experimental hall and on the internal rock walls





First results





Round Table "LUNA-MV at LNGS"
10th-11th February 2011

http://luna.lngs.infn.it/luna-mv

35 scientists from Europe, USA and Asia:

- Status of similar projects in Europe and USA
- Description of the LUNA MV project (site, machine, shielding,....)
- Astrophysical importance of the envisaged reactions
- Experimental open problems
- Discussion

Two documents:
A) Proceedings
B) Brief description of the project and list of "Working packages" to be distributed for adhesions (Aliotta, Fraile, Fulop , Guglielmetti)

Laboratory for Underground Nuclear Astrophysics

LUNA MV

Round Table: "LUNA - MV at LNGS"

February 10-11, 2011

- **STATUS OF SIMILAR UNDERGROUND PROJECTS**
  - Status of the Canfranc project, Luis FRAILE
  - The Bulby mine: an opportunity for underground nuclear astrophysics, Maria Luisa ALIOTTA
  - The Dresden Felsenkeller: A shallow underground option for accelerator – based nuclear astrophysics, Daniel BEMMERER
  - Status of the DIANA project, Alberto LEMUT
- **GENERAL DESCRIPTION OF THE LUNA-MV PROJECT**
  - The LUNA-MV project: from 2007 to now, Alessandra GUGLIELMETTI
  - A Megavolt Accelerator for Underground Nuclear Astrophysics, Matthias JUNKER
  - The Site for LUNA-MV at LNGS, Paolo MARTELLA
  - The Shielding of the LUNA-MV site, Davide TREZZI
- **PHYSICS CASES FOR LUNA-MV**
  - The $^{12}C(\alpha,\gamma)^{16}O$ reaction from the astrophysical point of view, Oscar STRANIERO
  - The rates of neutron – realeasing reactions in He-burning phases and their astrophysical consequences, Maurizio BUSSO
  - The seeds of the S-process: experimental issues in the study of $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$, Paolo PRATI
  - Towards the Gamow peak of the $^{12}C(\alpha,\gamma)^{16}O$ reaction, Roberto MENEGAZZO
  - Stellar helium burning studied at LUNA-MV. The $^{14}N(\alpha,\gamma)^{18}F$, $^{15}N(\alpha,\gamma)^{19}F$, $^{16}O(\alpha,\gamma)^{20}Ne$, and $^{18}O(\alpha,\gamma)^{22}Ne$, Daniel BEMMERER
- **DISCUSSION AND LAYOUT OF A POSSIBLE LOI EXTENDED TO OTHER GROUPS**
  - Workpackages towards European Underground Accelerator

Next-generation underground laboratory for Nuclear Astrophysics

Executive summary

This document originates from discussions held at the LUNA MV Roundtable Meeting that took place at Gran Sasso on 10-11 February 2011. It serves as a call to the European Nuclear Astrophysics community for a wider collaboration in support of the next-generation underground laboratory. To state your interest to contribute to any of the Work Packages, please add your name, contact details, and WP number under *International Collaboration*.

WP1: Accelerator + ion source

WP2: Gamma detectors

WP3: Neutron detectors

WP5: Solid targets

WP6: Gas target

WP7: Simulations

WP8: Stellar model calculations

Name	Institution	Work Package(s)
Carlos Abia	University of Granada	WP7
Maurizio Busso	Dept Physics & INFN-PG (Italy)	WP7
Gianpiero Gervino	INFN Torino	WP3 – WP3
Grigor Alaverdyan	Yerevan State University, Radio Physics Faculty, Yerevan 0025, Armenia	WP7: Stellar model calculations
Pierre Descouvemont	Universite Libre de Bruxelles	WP7
Sergio Cristallo	INAF – Teramo	WP7
Luciano Piersanti	INAF – Teramo	WP7
Sean Paling	Boulby Mine (UK)	No indication
Johan Nyberg	Uppsala University	WP2, WP3, WP6
Yi Xu	Institut d'Astronomie et d'Astrophysique, Universite Libre de Bruxelles, 1050, Brussels, Belgium	WP6 and WP7
D. Bemmerer et al.	HZDR	WP5
D. Bemmerer , Z. Elekes et al.	HZDR	WP6
Andrea Lavagno	Politecnico di Torino	WP7
Lian Gang	China Institute of Nuclear Energy	WP6
Andreas Zilges	Köln University	WP2
Sam Austin	NSCL/Mich St Univ	WP7
Antonino Di Leva	Napoli University	WP6
Gianluca Imbriani	Napoli University	WP2, WP7
Lucio Gialanella	Seconda Università di Napoli and INFN Napoli	WP6

THE LUNA COLLABORATION

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A.Formicola, M.Junker
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